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OBSERVER COMPENSATION FOR PROJECTIVE DISTORTION OF GRAPHIC DISP--ETC(U)

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OBSERVER COMPENSATION FOR PROJECTIVE DISTORTION OF GRAPHIC DISPLAYS

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Abstract

Graphic displays can provide accurate representations of three-dimensional space only if they are viewed from the geometric center of projection. Other viewing conditions result in distortions of virtual space. In our earlier reports we have proposed two processes by which the perceptual system discounts these distortions: an active compensation and a passive categorization. The present report describes 3 sets of studies which demonstrate the nature of these processes. In the first experiment, observers made magnitude estimate judgments of the depth of unfamiliar, 7-sided objects. Distortions were induced by moving the center of projection. Judgments corresponded almost completely with the distorted virtual space. In the second experiment, distortions were induced by moving the observer. No effect of the distortions were found in this situation indicating perfect perceptual compensation. These results replicate and extend our earlier findings.

In the second set of studies, observers made magnitude estimation judgments of the height, width and depth of familiar, rectangular, parallelopipeds. Distortions were induced as in the earlier 2 studies. Judgments did not correspond to the distorted virtual space, nor did they demonstrate any compensation. Results suggest that categorization of familiar objects affects perceptual compensation.

A third series of studies used the Up-Down Transformed Response method to estimate signal detection theory parameters. Judgments of familiar objects are not simply affected by response bias, rather we find that sensitivity to distortions of familiar objects is extremely low and highly variable within observers.

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Effective use of graphic displays requires that an observer be able to make accurate judgments based on displayed information. Ideally, questions regarding the use or design of graphic displays could be answered within the framework of traditional perceptual theory. It is increasingly clear, however, (cf. Rosinski and Farber, 1980) that the use of displayed information involves a complex interaction between perceptual processing and cognitive assumptions regarding the nature of pictoral representation. The ability to use simple visual information is greatly affected by assumptions regarding correct viewing conditions.

When one considers the perception of space depicted in pictures, this issue becomes interesting from both a theoretical and an applied perspective. From the standpoint of perceptual theory, the nature of picture perception is ambiguous. Originally Gibson (1951) and many of his colleagues interpreted the phenomena of picture perception as evidence for a direct theory of perception. Individuals were able to make accurate judgments of distance and depth in pictures; and there was a suggestion that under the right conditions, observers were apparently unaware that they had been viewing pictures. The interpretation offered for such results was that the array projected to the eye from a picture was identical to an array from the real world. Geometrically the information was the same in the two cases. Therefore, the same processes which were involved in the pick-up of information from the world could be used to pick up information projected from a photo. Pictures acted as informational surrogates for actual spatial layouts. Considerable evidence was accumulated regarding the equivalence

of pictures and real scenes, and this surrogate theory of picture perception was perhaps most influential over the last two decades.

Problems with such a view are fairly easy to point out. There is a geometric isomorphism between the pictorial and environmental arrays only when a picture is viewed from the correct center of projection. When a picture is viewed from some other place, the geometric relations which specify spatial layout are changed; the space specified by the picture is "distorted" in the sense that it does not correspond to the actual scene that was depicted. If space perception in pictures is simply and directly based on the information projected from the picture to the eye, such distortions should be evident in the perceived space. But this does not seem to occur. Pictured space does not seem to distort when we walk past the picture; we are usually unaware of the distortions present in studio photography; and artists and photographers have long known that it is often necessary to distort perspective to make a scene look right. In response to such difficulties with the surrogate theory, Gibson later (1979) argued that picture perception was very different from normal space perception, in that it was indirect and mediated by some interpretive mechanism. Hagen (1974) proposed that picture perception involved a totally different "mode" of perceiving (although she never really specified what a mode was, or how it was different in this case). Others such as Pirenne (1970) and Perkins (1973) suggested there was a compensation process which in some way was able to discount the effects of geometric distortions on perception.

From an applied perspective, the question of whether such compensation processes exist is important in display design. There is increasing use of two-dimensional displays of three-dimensional space

in such areas as simulation, master-slave robotics, remote piloting of aircraft and submersibles, and in multi-variable integrated displays. In each of these applications it is necessary that an operator respond to perceived space from a two-dimensional display. In the past, such devices have been based on the picture-as-surrogate-view of picture perception. Geometric accuracy (though not necessarily realism) has been an important aspect of display design. If there were a compensation process that affected the way that spatial information was used, a number of aspects of three-dimensional graphic displays would need to be revised.

An important research question then, is whether some compensation process exists which discounts the effects of projective distortion on space perception. We will simply assert here that there is no optical information available in the picture for the presence, absence, or extent of any projective distortion.

Extensive observations and demonstrations of this fact have been provided elsewhere (Farber and Rosinski, 1978; Rosinski and Farber, 1980). Inspite of the fact that distortion, in principle, is not specified independently, evidence does exist that observers are able to discount the effects of distortion. For example, both Rosinski (1979) and Rosinski, Mulholland, Degelman, and Farber (1980, in press) showed that projective distortions induced by magnification affect judgments of surface orientation under certain conditions, but not under others. These patterns of results seem to be reconcilable only in terms of some version of a compensation theory.

Distortions induced by magnification

The experiments discussed in this report examine the perceptual effects of projective distortions induced by magnification. In order to be able to discuss these effects we will briefly summarize the geometrical effects of magnification on represented space.

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Insert Figure 1 about here

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Figure 1 schematically depicts a side view of a pictorial projection. Points P and Q represent points in the world, perhaps corners of an object. If a picture is created by projecting P & Q to the center of projection O, these points map onto P* and Q* in the picture plane. If the eye is positioned at O, and the picture plane is moved, the environmental array specifies the location of P & Q in the world. With the picture plane present, the pictorial array specifies P and Q in virtual space. When the eye is at the center of projection, the environmental and pictorial arrays are identical, and virtual space corresponds to the world.

How can we characterize the distortions of space that result when the viewing point is changed? We adopt a simple convention based on Farber & Rosinski (1978). For any new viewing point one could describe the new virtual space which would have generated the new array. A comparison of the new virtual space with the original (or correct) virtual space gives a quantitative index of distortion. For example, in Figure 2, P and Q lead to a virtual space when viewed from O. If the photo is viewed from O', the array specifies a virtual space in

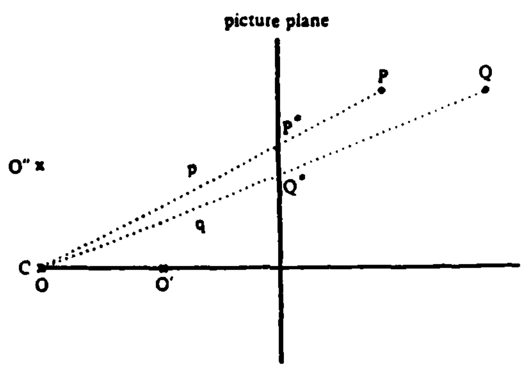

Figure 1. Schematic diagram illustrating how environmental points P and Q are projected into the picture plane points P* and Q*. C is the center of projection. O, O', and O" are the three observation points. The rays corresponding to P and Q (and to P* and Q*) are denoted by p and q.

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Insert Figure 2 about here

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which P' and Q' are closer together. When the viewing point is closer to the display than is the center of projection, we have magnification; this implies a compression of internal depth. We represent magnification and minification as the ratio of correct to actual viewing points. Thus, if one views from one-half the correct distance the magnification ratio is 2.0; if one views from twice the correct distance, the magnification ratio is 0.5. The changes in internal depth of objects in virtual space corresponds to the reciprocal of the magnification ratio. Thus, all internal depths are compressed by 1/2 under a 2-power magnification and, expanded by 2 under a 1/2-power minification. Similar descriptions of virtual space can be generated for lateral displacement of the viewing point. Lateral displacement results in a shearing of virtual space, and all dislocations of viewing point can be described as an additive combination of magnification and shear. The only thing to be stressed here is that these distortions are not due to any particular viewing point, but rather to the relation between actual and correct viewing point.

Since we can define the real space, can calculate virtual space, and can record judgments indicating perceived space, the experimental questions become quite simple. When does perceived space correspond to virtual space (the no-compensation hypothesis)? When does perceived space correspond to real space (the compensation hypothesis)?

As said before, there is no optical information for distortion, so the extent of distortion is not given solely by the photo. On

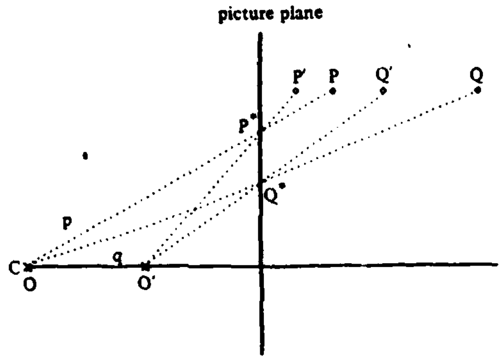

Figure 2. An illustration of the environmental compression produced by displacement of O to O'. P' and Q' represent the transformed environmental points.

what could compensation be based? One alternative is simply that one recognizes (in a pattern-match sense) a depiction, and that the pattern match criterion are extremely broad. Thus one might have categories for horizontal surfaces or right angles that are used even if the optic projection could not correspond to horizontal surfaces or right angles. A second alternative is a much more active compensation. Here we propose that the discrepancy between an actual viewing point and an assumed correct viewing point is evaluated, and thus is used to discount the effects of geometric distortion.

The experiments reported here provide demonstrations of both of these types of compensation, and of the conditions in which they operate. For judgments involving the sizes of unfamiliar objects, pictorial compensation is based on the discrepancy between the actual and an assumed correct viewing point. For familiar objects, assumptions about the nature of the object reduce sensitivity to distortions of virtual space.

Experiment 1

In our previous research on this project we have shown the conditions under which an active compensation process operates in a task involving the perception of displayed orientation. We found that when magnification is induced by changing the center of projection while varying the viewing position, judgments approximated those expected on the bases of the geometry of virtual space. Under such presentation, there is neither optical nor non-optical information for the presence or extent of distortion. If the judged targets are totally unfamiliar, there is no basis for perceptual judgment other than the geometric projection. One would expect, therefore, that

judgments should most closely correspond to the dimensions of virtual space. Experiment 1 examines this prediction for judgments of the internal depth of unfamiliar objects. As noted above, magnification results in a compression of virtual space, and minification results in an expansion of virtual. The exact geometric effects expected under the conditions used in this experiment are presented in Figure 3.

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Insert Figure 3 about here

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If judgments were totally determined by the optic projection, we would expect obtained data to be in close correspondence to the functions depicted in Figure 3.

Method

Observations. Six paid, adult volunteers (3 men, 3 women) served as participants in the research. All individuals had visual acuity of 20/40 Snellon (corrected) or better, and those who normally wore corrective lenses did so during the experiment. Participants made two judgments of internal depth for each of seven objects under five different projection conditions for a total of seventy judgments per observer.

Apparatus. The stimulus objects were computer-generated graphics displayed on a CRT screen (P-31 phosphor). The objects themselves consisted of a series of concentric, irregular, five-sided geometric objects (5-gons). Corresponding vertices of each of the 5-gons were connected by lines to increase linear perspective information. In all cases, the geometric center of the series of 5-gons was centered on the

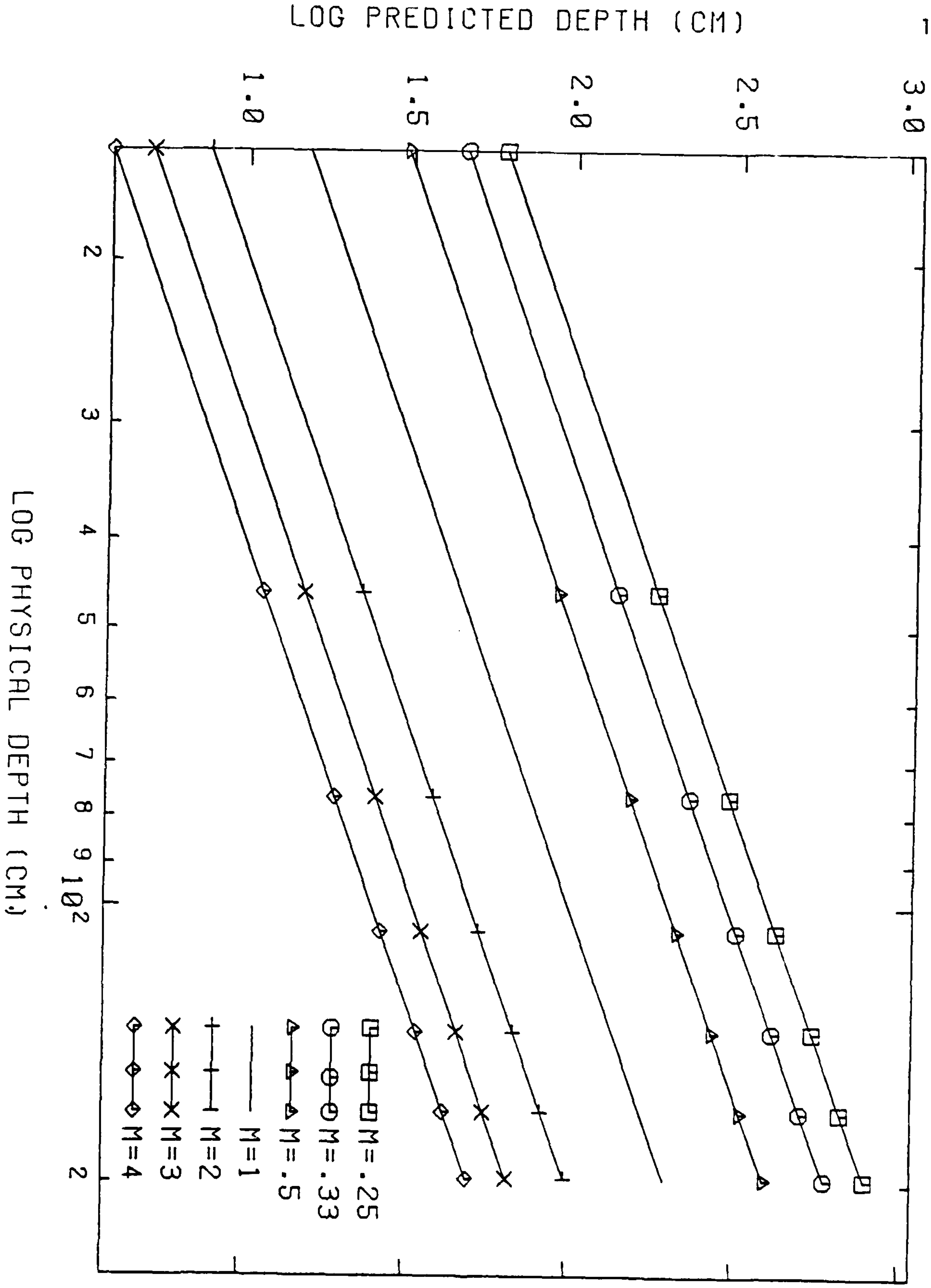

Figure 3. Distribution of virtual space for the magnification conditions in Experiments 1 and 2.

screen and on the line of sight of the observer. The overall impression was of looking through an irregularly shaped "tunnel" which receded into the distance. The length (i.e., internal depth) of the tunnels was logically defined to vary over values of 17.5, 52.5, 87.5, 122.5, 157.5, 192.5, and 227.5 cm. Regardless of the defined length of the tunnel, each one was defined using only 5 concentric, 5-gons. Thus the number of segments of the tunnel did not vary with its length.

Across conditions these tunnels were displayed so that the geometric center of projection of the screen images was located at 28, 56, 112, 225, and 337 cm. from the screen. The experimental participants viewed the screen binocularly, with their head held by an opthalmic chin stand, from a viewing point 112 cm. from the screen. Such viewing conditions result in magnifications of 0.25, 0.50, 1.0, 2.0, and 3.0 respectively.

The conduct of the experiment was computer controlled. A program at the command monitor level controlled the order of conditions for each observer. The experimental program presented the displays in random order, controlled the number of presentations, and recorded responses.

Procedure. When each observer logged on to the laboratory computer system, he/she was automatically connected to the experimental control program. The appropriate condition was selected, instructions displayed, and a sample stimulus (not used in the experiment proper) was displayed. In all conditions, subjects were to make modulus-free magnitude estimates of the internal depth of the tunnels. Judgments were

entered on a keyboard connected to the laboratory computer. When the return key was pressed, the stimulus was removed, a mask of 200 connected, randomly-oriented lines was presented for 1/60 sec. to reduce screen persistence effects (and prevent direct stimulus comparison), and the next stimulus (randomly determined) was presented. Thus the rate of presentation was totally controlled by the observer. At any time during the experiment, observers could cease participation by pressing an escape key.

Results and Discussion

The magnitude estimates of internal depth were subjected to a logrithmic transform to restore homogeneity of variance, and to linearize the underlying power functions. The geometric mean magnitude estimate as a function of physical depth is presented in Figure 4.

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Insert Figure 4 about here

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The transformed data were subjected to a 6 (subjects) X 5 (magnification condition) X 2 (repetitions) X 7 (depth) analysis of variance with repeated measures on the last three factors.

There was a statistically significant effect of physical depth on judgments, $\underline{F}$ (6,30) = 112.05, $\underline{p} < .01$. This effect merely indicates that there is a direct correspondence between physical and perceived space. Judgments in the present situation are clearly based on the visual texture and perspective information provided by the tunnels.

There was also a significant effect of magnification condition, $\underline{F}$ (4,20) = 34.52, $\underline{p} < .01$. As magnification increased, perceived depth

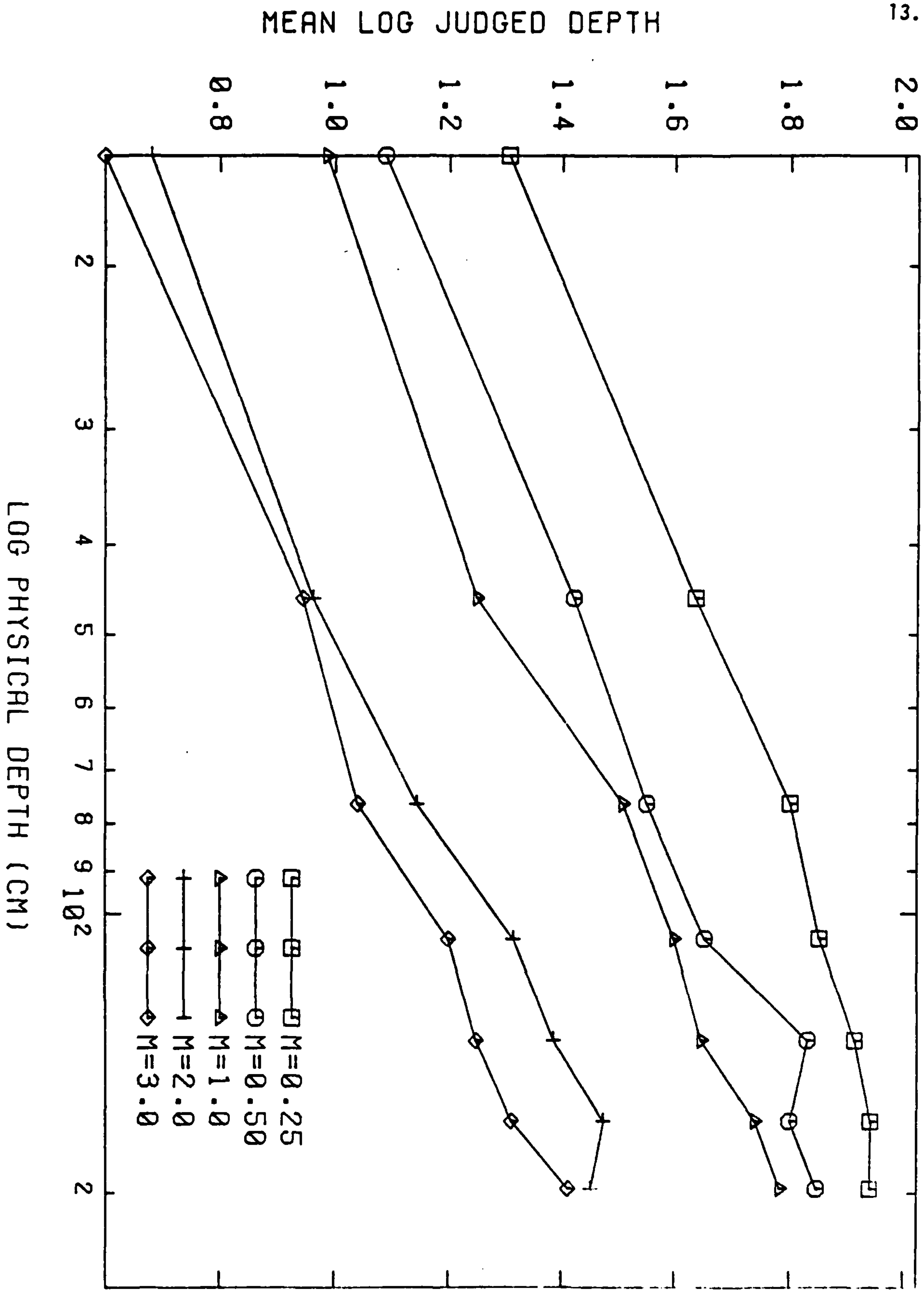

Figure 4. Mean judged depth as a function of physical depth with magnification as a parameter (Experiment 1).

was expanded. This is in accordance with expectations based on the geometric transformation of virtual space. The interaction between physical depth and magnification was not significant, $\underline{F}$ (24,120) = 1.12, $\underline{p}$ < .05. Again this is a result that is in correspondence with the expectations based on the geometry of virtual space. The transformation induced by magnification is a simple, linear rescaling of space. The absence of a depth by magnification interaction indicates that, in the experiment, perceived space is linearly altered over magnification. No other main effects or interactions in the analyses were significant (all $\underline{p}$'s > .05).

In a log-log coordinate system, the slope and intercept of a function correspond to the exponent and coefficient, respectively, of the underlying power function. The values for the expression $y = bx^m$ are given in Table 1. Inspection of this table reveals the

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Insert Table 1 about here

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close correspondence between virtual and perceived space. If perceived depth were totally determined by the geometric information available, judged and virtual depth should be isomorphic within the limits imposed by observer constant error. Early demonstrations of such isomorphism (cf. Purdy, 1960) have been taken as evidence of the necessity and sufficiency of geometric information for spacial vision.

We can see that in the present experiment a close relationship exists between the obtained data and predictions based on the virtual space. Since magnification is a linear transformation, it should not affect the power function exponent. We can see in Table 1 that this

Table 1

Coefficient and exponents for the power function for each magnification condition in Experiment 1. Center of projection moved, viewing point constant. ($y = bx^m$)

Magnification	Coefficient	Exponent
0.25	4.67	0.58
0.50	1.86	0.69
1.00	1.32	0.72
2.00	0.60	0.73
3.00	0.61	0.70

is the case. Across all five conditions, exponents are essentially stable. If there were a perfect isomorphism between judged and virtual space, we would expect a constant exponent of 1.0, indicating a linear psychophysical function. In fact, the obtained functions have exponents consistently less than 1.0. We suggest that this may be attributed to two factors: first, the conditions of the experiment may have resulted in less than perfect correspondence. Since viewing was binocular of a planar surface, stereopsis and accommodative convergence may have resulted in a cue conflict with the perspective information. Some version of a weighted-mean resolution of the conflict would result in a series of exponents less than 1.0. A second possibility is that the information pick-up mechanism itself is not linear. A variety of other experiments (see Marks, 1974 for a review) have consistently found that judgments increasingly underestimate space as distance increases. This may account for the factional exponent found in many experiments using different forms of visual information.

The close relationship between perceived and virtual space can also be seen in an examination of the coefficients represented in Table 1. Ideally the coefficient should equal the inverse of the magnification ration since the magnification simply results in a linear re-scaling. Although there is some constant error, perceived space closely matches the expected expansion and contraction of virtual space. The single exception to this is in the m = 3.0 condition. The lack of any difference between a 2-power, and a 3-power compression of space may simply reflect the existence of a floor effect.

To summarize, the basic finding of this experiment is that there exists a close relationship between judged and virtual space under magnification, when there is no optical or non-optical information for the transformation.

Experiment 2

A discrepancy between the actual viewing distance of a display and the distance of the center of projection results in optical magnification. The preceeding experiment demonstrates conclusively that large perceptual effects result if a display is not viewed from the center of projection. There is an apparent paradox here. Substantial evidence exists (See Farber and Rosinski, 1978, for a review) that indicates that human observers are able to discount, or compensate for such distortions. At least under some conditions, optical distortions do not appear to affect perceived space. It has been suggested (Rosinski, 1979; Rosinski and Farber, 1980) that such compensation processes are based on the registered discrepancy between the actual and an assumed correct viewing point. For judgment of orientation, for example, magnification does not affect perception if the degree of distortion is related to actual viewing distance.

To determine whether pictoral compensation process could operate within the context of the perception of unfamiliar objects, Experiment 2 investigated the effects of distortion produced in different ways.

Magnification can be defined as the ratio of the center of projection distance (D_{cp}) to the viewing point distance (D_{vp}). There are then two ways to generate optically equivalent distortions: moving the center of projection while maintaining constant viewing distance

as in Experiment 1; or moving the viewing point while maintaining a constant location for the center of projection. In this latter case, the degree of magnification (and of the expansion or contraction of virtual space) is perfectly correlated with viewing distance. Under such conditions, a non-optical basis for compensation exists, and we have found elsewhere (Rosinski, 1979) that distortions do not effect perception of surface orientation. Experiment 2 explores whether compensation can occur for distortions of virtual depth.

Method

Across all conditions the geometric center of projection was located 112 cm. away from the screen. Magnifications were induced by moving the location of the viewing point. In various conditions the viewing point was located 28, 56, 112, 225, or 337 cm. from the screen, resulting in magnification ratios of 4.0, 2.0, 1.0, 0.5, 0.33, respectively. Distortions of virtual space for these magnifications are shown in Figure 3.

All other details of method and procedure were identical to those in Experiment 1.

Results and Discussion

A log-log plot of the mean magnitude estimates is given in Figure 5. Physical depth of the tunnels is plotted along the x-axis and

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Insert Figure 5 about here

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magnification ratio is treated as a parameter. A 6 (subjects) X 5 (magnification) X 2 (repetition) X 7 (depth) completely factorial

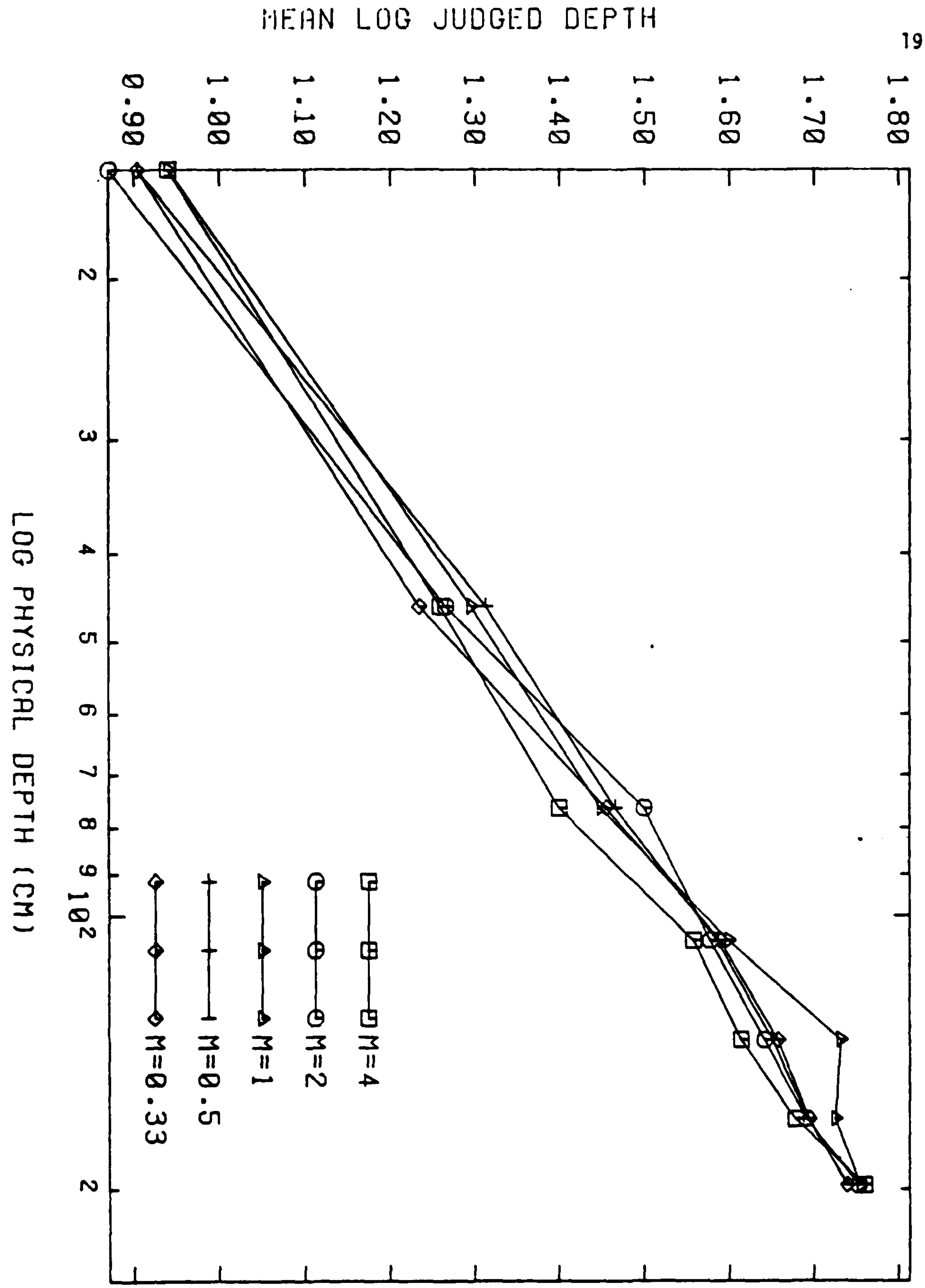

Figure 5. Mean judged depth as a function of physical depth with magnification as a parameter (Experiment 2).

analysis of variance was performed on the log transformed magnitude estimates.

There was a significant effect of physical depth on judgment, $F(6,30) = 86.63$, $p < .01$. This again merely indicates that differences in physical size affect perception. There was, in addition, a marginally significant effect of repetition, $F(1,5) = 2.50$, $p < .01$. The mean magnitude estimate in the first repetition was 28.8, the mean for the second was 30.9. Although this is a statistically significant difference, we attach no theoretical or empirical importance to it. Most important, there was no effect of magnification condition on judgment, $F(4,20) = 0.48$, $p > .05$. Since magnification ranged from 0.33 to 4.0 across conditions, distortions changed the size of virtual space by a factor of 12. No difference is evident in judgment, and we must conclude the compensation was perfect and complete. No other main effects or interactions were significant, all p's $> .05$.

The extent to which the observers were able to compensate for or to discount the effects of magnification can be seen in an examination of the coefficients and exponents for the power functions describing these data. These values for each magnification condition are given in Table 2. Perfect isomorphism would require an exponent of 1.0; as

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Insert Table 2 about here

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in Experiment 1, these exponents are consistently below 1.0, indicating some non-linearity in the use of visual information in making perceptual judgments. The values of the coefficients are most revealing. Magnification causes a compression or expansion of virtual space. If

Table 2

Coefficients and exponents for the power functions for each magnification condition in Experiment 2. Center of projection constant, viewing point moved. ($y = bx^m$)

Magnification	Coefficient	Exponent
0.33	1.02	0.77
0.50	1.12	0.74
1.00	1.09	0.76
2.00	1.04	0.78
4.0	1.17	0.72

virtual space determined perceived space the coefficients should equal the reciprocal of the magnification ratio. Instead of this pattern, we see evidence for total compensation. Regardless of the twelve-fold distortion of space, power function coefficients are constant.

In summary, the results of Experiment 2 conclusively show that pictorial compensation for magnification exists. Observers are able to completely discount the effects of dislocation of the viewing point. Since this compensation exists when distortion is correlated with viewing distance, we suggest that a comparison between the actual viewing distance and some internal standard forms the basis of compensation.

Experiment 3

It is clear that an observer can actively discount the effects of optical transformation. A second possible mechanism has been proposed in our earlier work. It would appear that under some conditions people simply do not notice, or are not aware that a distortion exists. We distinguish this from a more active discounting process in that a simple failure of discrimination or less of sensitivity appears to be involved.

Perceptual judgments of spatial layouts can involve two different activities. One is the registration and use of spatial information. A second may simply involve a perceptual categorization or pattern match of an object. Thus one might categorize a familiar object and make judgments based on assumptions regarding the known qualities of the object. If, for example, someone is identified as a familiar person, judgments of their size or dimensions may depend less on infor-

mation for virtual space than on previously known characteristics. This is apparently the basis for the well-known Honi phenomenon of social cognition.

Perkins (1973) has suggested a similar basis for compensation. Once an object meets certain minimal criteria for categorization, distortions of the virtual object may be difficult to detect. We propose that such a compensation process is distinguished in two ways. First, it depends on a pattern match or categorization of a familiar object. Second, the lack of an effect of distortions of virtual space is due to a failure of discrimination, or decreased sensitivity and not to an active computational process that discounts the effects of geometric transformation.

To explore this type of effect we conducted two experiments that were analogous to Experiments 1 and 2 above. Distortions were induced either by moving the center of projection with a constant viewing point or moving the viewing point while keeping the center of projection constant. In experiment 3 subjects made judgments of the dimensions of square parallelopipeds when the center of projection was moved across condition. Our earlier experiments (Experiment 1 above as well as those reported earlier) indicate that such presentation conditions should lead to relatively close correspondence between judgments and virtual space. Departures from such correspondence will provide an index of the degree to which perceptual categorization effects spatial judgments.

Method

Observers. Six paid, adult volunteers (3 men, 3 women) served as participants in the present study. All individuals had visual acuity

of 20/40 Snellen (corrected) or better, and those who normally wore corrective lenses did so in the experiment. Participants made 49 perceptual judgments in each of 4 blocks for each of three object dimensions under each of seven magnification ratios for a total of 4,116 judgments per observer.

Apparatus. The stimuli were computer-generated graphics displayed on a CRT. A series of square parallelopipeds (rectangular solids of equal length and width) ranging in size from 1 cm X 1 cm X 1 cm to 16 cm X 16 cm X 16 cm was logically defined in the computer's display space. Dimensions selected from this range varied in seven equal steps; although length and width were equal, their values were varied independently of the height of the object. Thus there were 49 stimulus objects. Five equally spaced lines were drawn on the top and on one side of each of the objects to maximize linear perspective information. Each object was subjected to two successive Euler transforms so that the two sides were at a 45° angle to the screen and the top was at 10° to the screen. Such an arrangement gives good 3-point perspective.

Across conditions the objects were displayed such that the geometrical center of projection of the screen images was located at 28, 56, 84, 112, 225, 337, or 450 cm from the screen. The experimental participants viewed the screen binocularly, with their head held in an opthalmic chin stand, from a viewing point of 112 cm from the screen. These viewing conditions result in magnifications of 0.25, 0.50, 0.75, 1.0, 2.0, 3.0, 4.0. The geometric effects of such magnifications on the objects' virtual height, width, and internal depth are depicted in Figures 6 through 11. These figures represent virtual space relations

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Insert Figures 6 through 11 about here

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in linear coordinates with an arbitrary scale derived from the graphics hardware. This scale, however, is isomorphic with a scale of cm under a transform of 40 units to 1 cm.

Design. Each subject made modulus-free magnitude estimation judgments of the object's height, the width of one side, and of the internal depth (defined as the distance between the front and rear corners of the top surface). The dimension to be judged, and the other dimension of the object were varied orthogonally to isolate any context effects. Thus each value of the height (for example) was paired with each of the seven values of the other dimension in each of the four blocks. The statistical design then was a 6 X 7 X 3 X 4 X 7 X 7 complete factional, mixed-effects analysis of variance.

Procedure. When each observer logged on to the laboratory computer system, he/she was automatically connected to the experimental control program. A program at the command monitor level controlled the counterbalancing of conditions, and a separate program presented the displays in random order, controlled the organization of the trial blocks, and recorded responses. For each trial block, the appropriate condition was selected and instructions were displayed which verbally and graphically instructed the subject as to which dimension was to be judged. Judgments were entered on a keyboard connected to the laboratory computer. When the return key was pressed, the stimulus was removed, and a mask was displayed for 1/60 sec to reduce screen persistence effects.

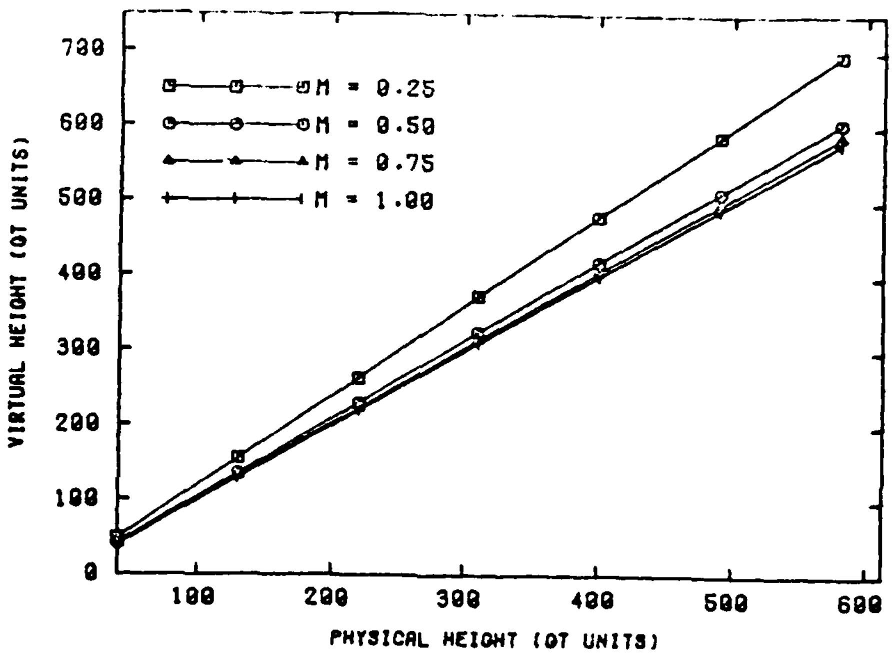

Figure 6. Effects of minification on virtual height of objects in Experiment 3.

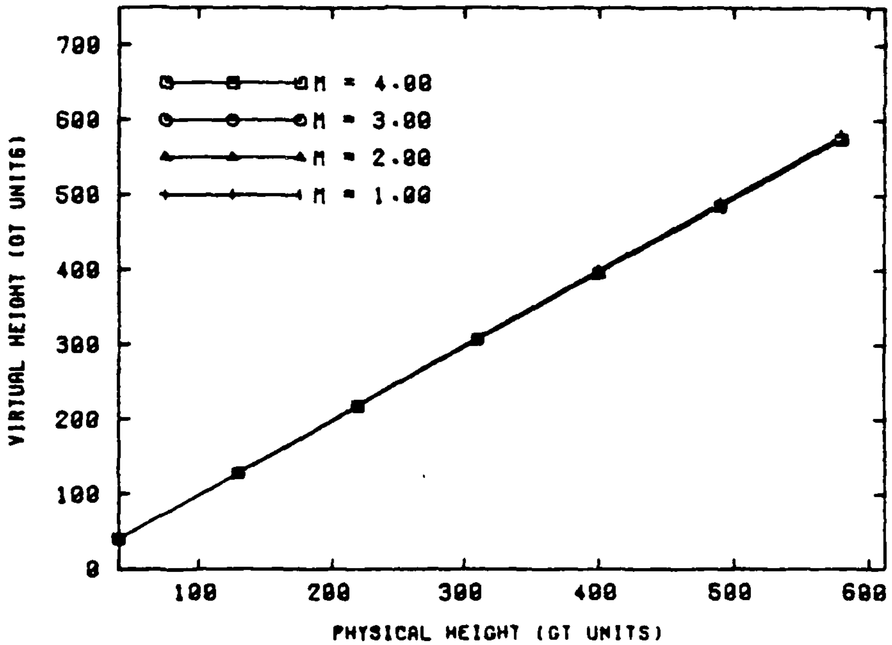

Figure 7. Effect of magnification on virtual height of objects in Experiment 3.

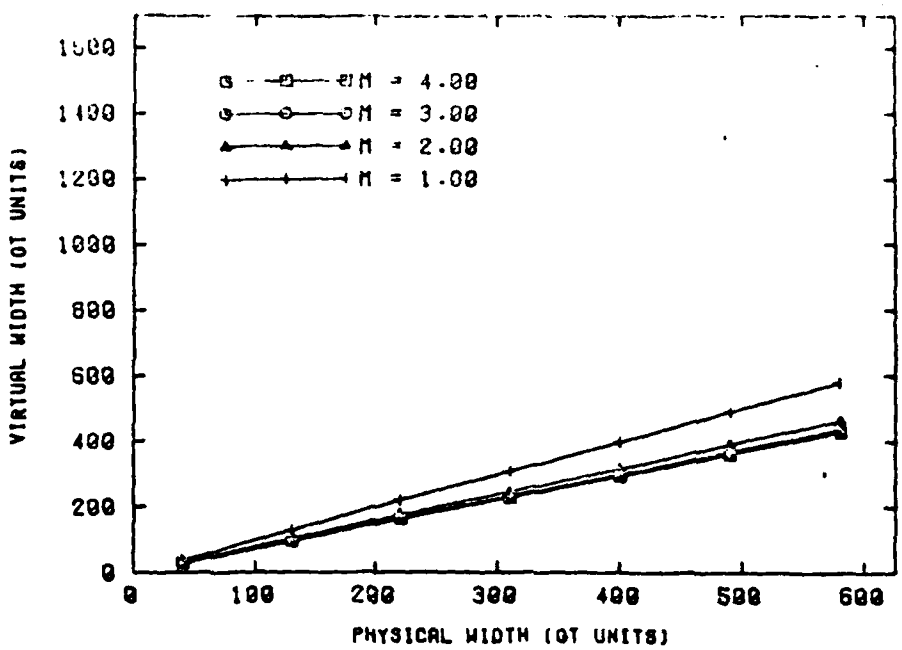

Figure 8. Effect of minification on virtual width of objects in Experiment 3.

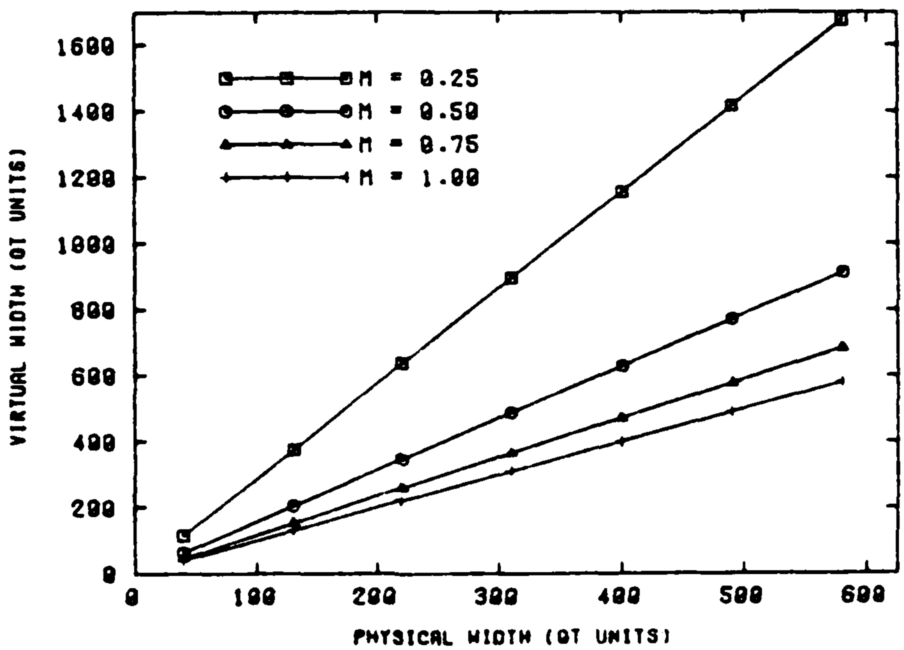

Figure 9. Effect of magnification on virtual width of objects in Experiment 3.

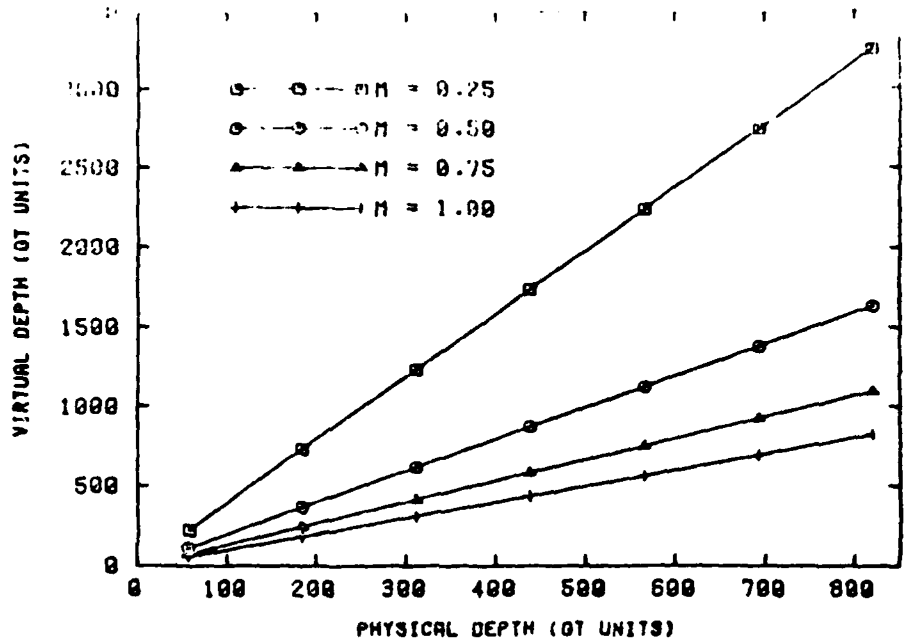

Figure 10. Effect of minification on virtual depth of objects in Experiment 3.

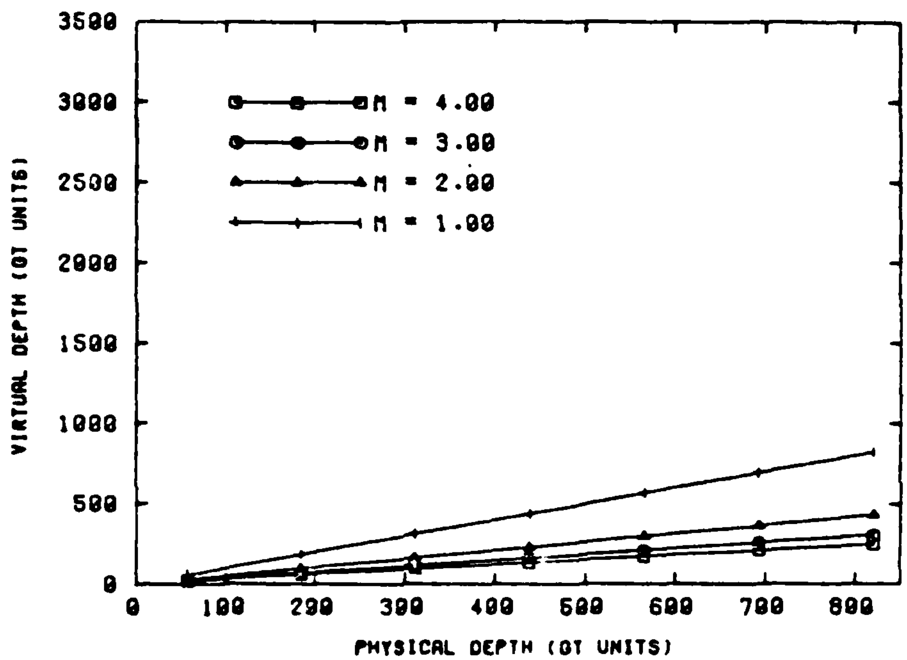

Figure 11. Effect of magnification on virtual depth of objects in Experiment 3.

This mask consisted of seven parallelopipeds superimposed with a common vertex. The rate of trial presentation was totally controlled by the observer. At any time during the experiment an observer could cease participation by pressing an escape key. Because of the large number of judgments required, the experiment could not be completed in one session. No attempt was made to impose a schedule on the participants. Rather sessions were scheduled at their convenience.

Results and Discussion

All judgments were log transformed to restore homogeneity of variance of the underlying magnitude estimates. The obtained data for judgments of height, width, and internal depth is depicted in Figures 12, 13, and 14. An analyses of variance on the transformed scores

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Insert Figures 12, 13, and 14 about here

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revealed a significant effect of physical size, $F\ (6,30) = 61.09$, $p < .01$. Increasing physical size corresponds to increases in judgment. There was also a marginal effect of dimension judged, $F\ (2,12) = 3.21$, $p < .10$. The dimension of height was consistently overestimated compared to the width and depth. There was also significant interaction between the dimension judged and the size of the irrelevant dimension, $F\ (12,78) = 3.30$, $p < .01$. Judgments of object height were increasingly over-estimated as the irrelevant width dimension was increased. Judgments of width and depth, on the other hand, were increasingly underestimated as the irrelevant height dimension increased. Thus it seems that the size of independent dimensions is not judged independently when the

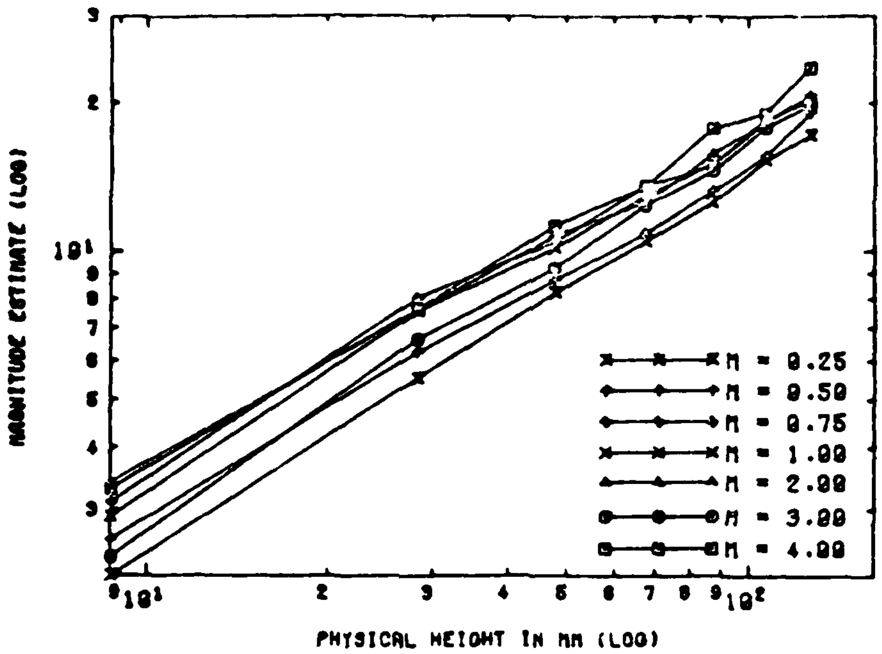

Figure 12. Mean judged height as a function of physical height with magnification as a parameter (Experiment 3).

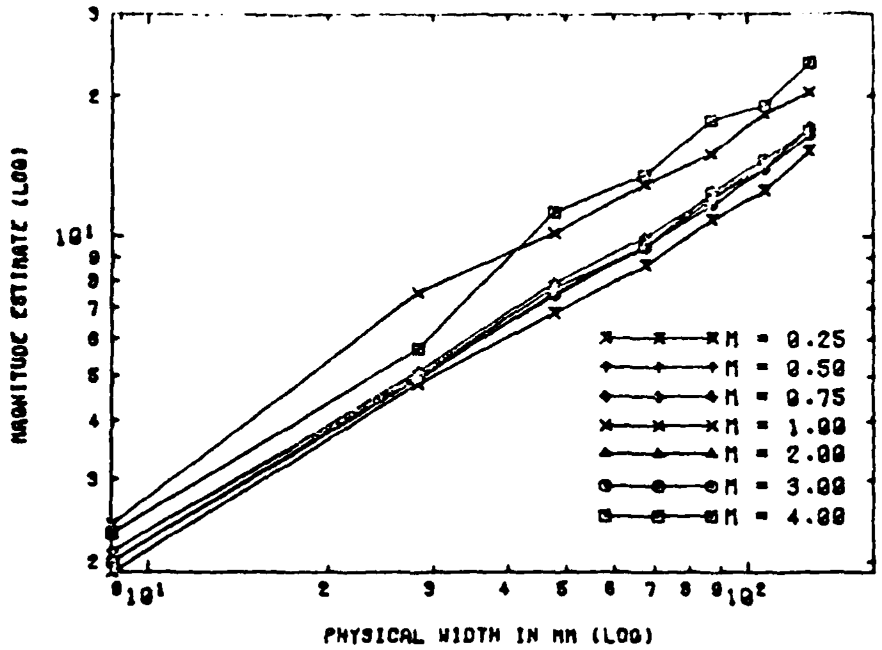

Figure 13. Mean judged width as a function of physical width with magnification as a parameter (Experiment 3).

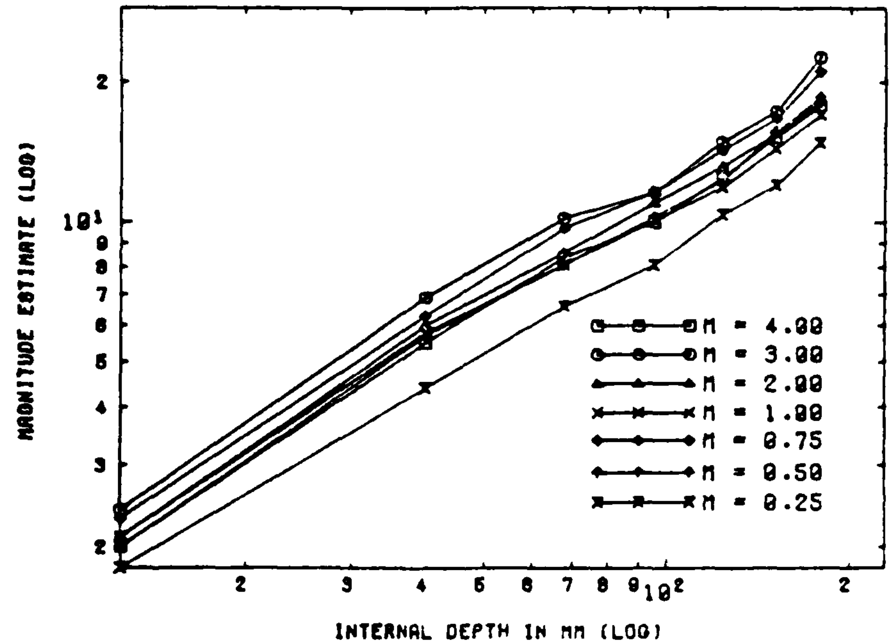

Figure 14. Mean judged depth as a function of physical depth with magnification as a parameter (Experiment 3).

target object is familiar. This suggests that judgments are not simply based on visual information, but also on some interdimension consistency. There was non-significant effect of projection condition, $\underline{F}$ (6.36) = 1.95, $\underline{p} > .05$. Optical distortion exerted little effect on judgment.

The degree to which distortions of virtual space affected judgment is also evident in Table 3. As in the earlier two experiments discussed

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Insert Table 3 about here

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above, the exponent of the power function is stable, and consistently below 1.0. Again, underestimation increases with size. More revealing in the present case is an examination of the coefficients. The virtual size of dimensions that are parallel to the screen is not affected by magnification (see Farber and Rosinski, 1978). Since the height of the object is based on a surface nearly parallel to the screen surface, we should expect no effects of magnification. Indeed there appears to be no consistent relations between magnification and coefficients. For the judgment of depth, the coefficients should be in inverse relation with the magnification ratio. As in Experiment 1, a magnification compresses depth and the extent of this compression should be revealed in these coefficients. Width is an intermediate case between the two, ideally the coefficients would be related to a tangent function of the magnification ratio. The striking thing here is that none of these geometric predictions are upheld. All coefficients for all judgments are fractional, and none change with

Table 3

Coefficients and exponents for the power functions for judgments of height, width and depth at each magnification condition in Experiment 3.

Magnification	Coefficient	Exponent
	Height	
0.25	0.42	0.77
0.50	0.54	0.72
0.75	0.72	0.69
1.00	0.65	0.71
2.00	0.77	0.68
3.00	0.46	0.79
4.00	0.67	0.73
	Width	
0.25	0.37	0.76
0.50	0.39	0.78
0.75	0.40	0.76
1.00	0.45	0.76
2.00	0.35	0.79
3.00	0.35	0.79
4.00	0.43	0.76
	Depth	
0.25	0.27	0.76
0.50	0.28	0.80
0.75	0.32	0.79
1.00	0.32	0.76
2.00	0.30	0.79
3.00	0.34	0.79
4.00	0.27	0.80

changes in the magnification ratio. Although judgments change with increasing object size, judgments are not in correspondence with the virtual space. We suggest that judgments are affected by the categorization of the object as a square parallelopiped, and that this pattern match may reduce sensitivity to distortions of virtual space.

Experiment 4

We do not take the results of Experiment 3 as evidence of active compensation, accuracy is not restored over the transforms. Instead it would appear that virtual space is ignored. A question arises as to whether observers could compensate for these distortions, if the optical transformation was correlated with viewing distance (as it was in Experiment 2). It might be argued that Experiment 3 presented no optical or non-optical information for the distortion and consequently observers relied on object similarity, or on assumptions about the object in making their judgments. Providing information for the distortion might then reveal the action of an active compensation. If, however, categorization of familiar objects reduces the observer's sensitivity to distortion, evidence of compensation should not be found under these conditions. Experiment 4 evaluates these lines of reasoning.

Method

In this experiment, the center of projection was positioned at 112 cm away from the screen in all conditions. Magnifications were created by moving the viewing point to 28, 56, 84, 112, 225, 337, or 450 cm away from the display. Such viewing conditions result in magnifications of 4.0, 3.0, 2.0, 1.0, 0.75, 0.50, and 0.25 respectively.

All other details of method and procedure were identical to those in Experiment 3.

Results and Discussion

The data were log transformed. The results for judgments of height, width and depth are depicted in Figures 15 through 17. They are

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Insert Figures 15 through 17 about here

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represented in log-log coordinates with magnification as a parameter. Analysis of variance revealed a significant effect of physical size, $\underline{F}$ (6,30) = 190.96, $\underline{p} < .01$. Again, magnification condition did not significantly affect judgment, $\underline{F}$ (6.36) = 1.83, $\underline{p}. > .10$. Although object size affected judgments, distortions of virtual space did not. None of the sixty other main effects or interactions were statistically significant.

Table 4 presents the power function coefficients and exponents for this experiment. Once again, the coefficients are fractional, and bear

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Insert Table 4 about here

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no relationship to magnification ratio. This similarity of these results to those in Experiment 3 indicates that regardless whether magnification is correlated with viewing distance, judgments of familiar objects do not differ. One further characteristic needs to be noted.

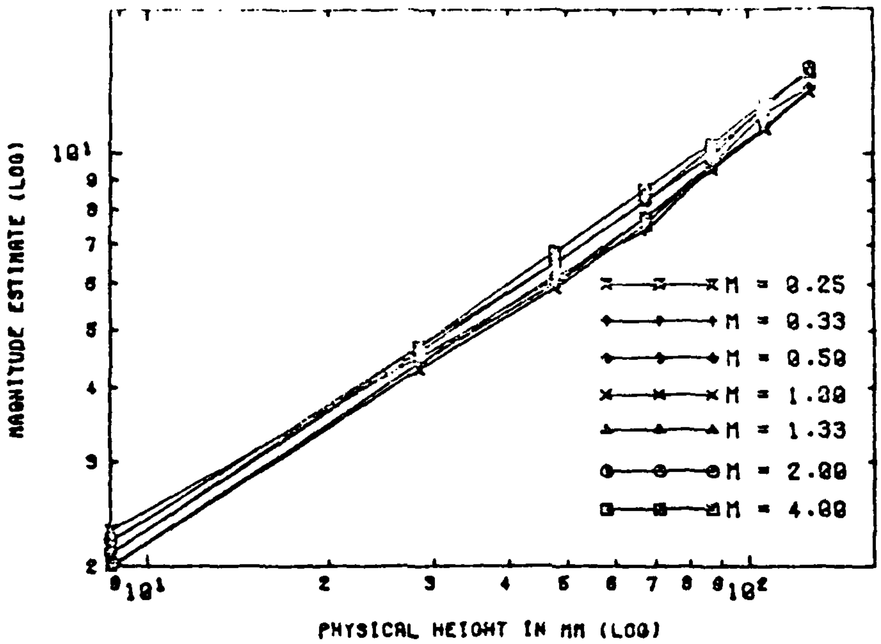

Figure 15. Mean judged height as a function of physical height with magnification as a parameter (Experiment 4).

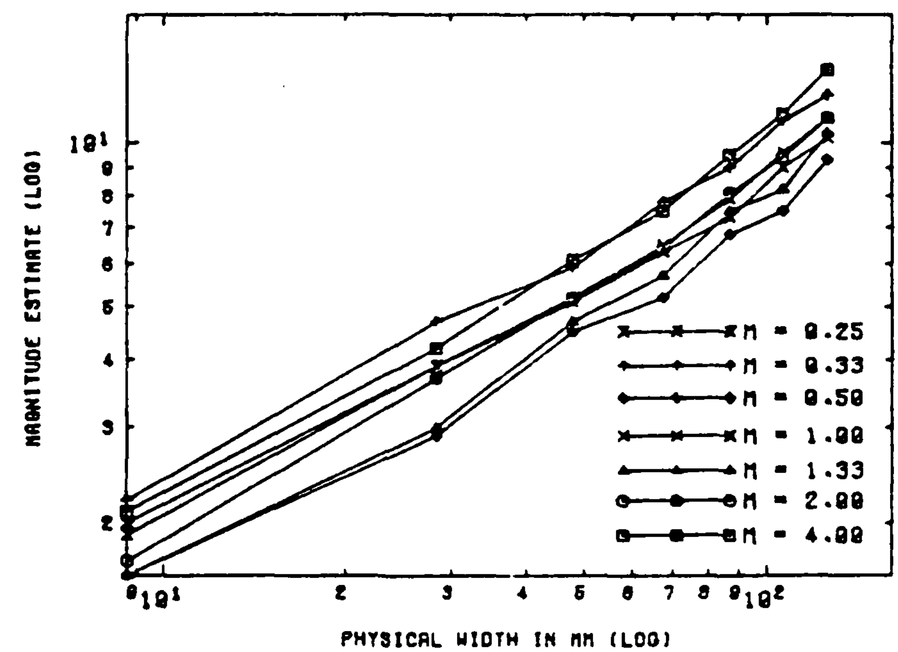

Figure 16. Mean judged width as a function of physical width with magnification as a parameter (Experiment 4).

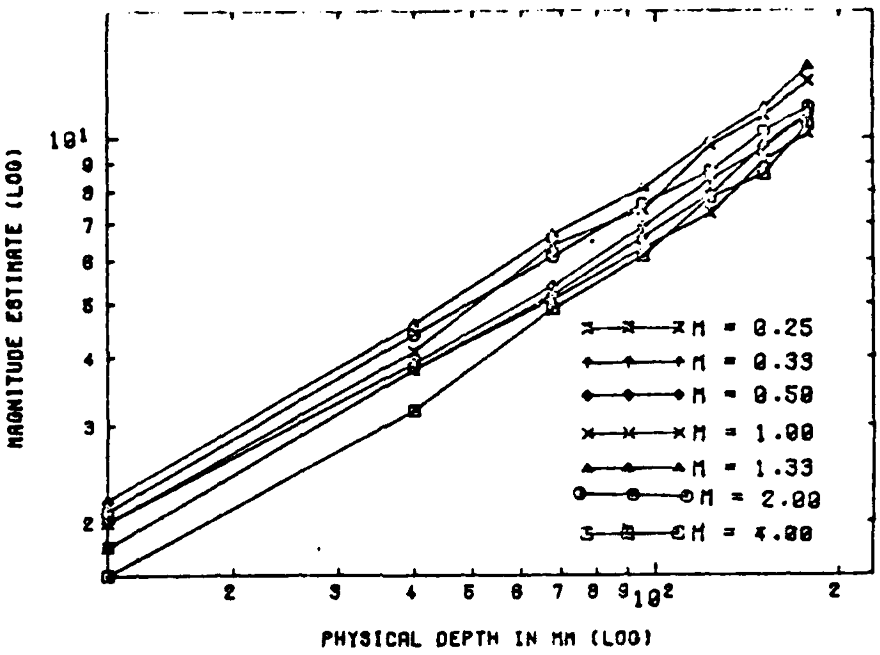

Figure 17. Mean judged depth as a function of physical depth with magnification as a parameter (Experiment 4).

Table 4

Coefficients and exponents of the power functions for judgments of height, width, depth in each magnification condition in Experiment 4.

Height

Magnification	Coefficient	Exponent
0.25	0.50	0.61
0.50	0.54	0.64
0.75	0.36	0.65
1.00	0.48	0.63
2.00	0.32	0.70
3.00	0.37	0.69
4.00	0.45	0.69

Width

Magnification	Coefficient	Exponent
0.25	0.42	0.70
0.50	0.46	0.68
0.75	0.44	0.69
1.00	0.56	0.63
2.00	0.45	0.70
3.00	0.50	0.68
4.00	0.44	0.71

Depth

Magnification	Coefficient	Exponent
0.25	0.37	0.63
0.50	0.39	0.63
0.75	0.31	0.68
1.00	0.34	0.69
2.00	0.39	0.68
3.00	0.44	0.63
4.00	0.27	0.69

The designs of Experiment 3 and 4 were statistically extremely powerful, with 4,116 judgments per experiment. The absence of magnification effects in both studies can be taken as a highly reliable finding.

In summary, it would appear that perception of familiar pictured objects is little affected by distortions of virtual space. Although we have showed that such distortions affect judgment in Experiment 1, categorization of familiar patterns interferes with sensitivity to distortion. Judgments are apparently based on assumptions regarding the nature of the object.

Experiment 5

In order to directly test one of the implications of the previous two studies we attempted to measure the observer sensitivity (d') to distortions of familiar objects. In fact, sensitivity turned out to be so low, that we had substantial difficulties in measuring it. Although the data gathered in this series of experiments must be regarded as preliminary, or pilot data, the problems as well as the results are themselves instructive.

Method

The graphic display apparatus and the target objects used in Experiments 3 and 4 were used in this series. A modified-staircase procedure was used to assess the amount of distortion of virtual space which corresponded to a d' of .707. Since d' is equal to the separation between the underlying signal and signal plus noise distributions, a staircase procedure essentially changes the strength of the signal plus

noise distribution to track a constant value of d'. In the present instance this means that an object of specified degree of distortion was displayed. The observer simply responds with a yes-no regarding the presence of distortion, and decision rules in the program determine the amount of distortion to be displayed on the next trial.

Procedure. Details of procedure were essentially similar to those described in Experiment 3. The major difference was that subjects made yes-no judgments as to whether the displayed object was a square parallelopiped. In general, a no response increased the amount of distortion, while two successive yes responses decreased the amount of distortion presented in the next trial. The initial experiments of this series are best regarded as pilot studies and will be reported as such.

Results and Discussion

Experiment 5a. In this experiment a stimulus object was randomly drawn from the set of 49 constructed for Experiment 3 and displayed to an arbitrary center of projection while the subject viewed the screen from 112 cm. Each observer was simply to respond whether the object looked distorted or not. Successive stimuli were drawn from the same pool of 49 objects with replacement. Thus over trials, degree of magnification was directly controlled and all other factors were allowed to randomly vary. Four subjects were run through approximately 30 repetitions of the staircase procedure. No estimate of sensitivity was possible. All subjects in all trials repeatedly responded that no distortion existed. Even with a 30-fold magnification which compresses virtual internal depth to 1/30 of its defined value, no distortion was reported.

Experiment 5b. This experiment was equivalent to 5a, except that subjects were instructed that the three surfaces of the object must meet at right angles, otherwise the object was distorted. Again, no estimate of sensitivity was possible.

Experiment 5c. Subjects were given more stringent criteria for distortion. A rectangular object was defined as one which had surfaces meeting at right angles, had opposite parallel edges, and whose diagonals on each side were identical in length. Although the subjects attempted to judge based on these criteria, the responses were highly variable, and the program did not track any consistent value.

Experiment 5d. In an attempt to make the discrimination between distorted and non-distorted objects easier, only a single object - a cube - was used. Thus all stimulus presentations were identical in all respects except for the amount of magnification or minification. Again no consistent tracking with a test sequence took place.

Experiment 5e. To make the discrimination easier still, the entire design was changed from a simple yes-no paradigm to a two-alternative forced-choice. Pairs of cubes were presented successively. One cube was undistorted (i.e., was projected to the viewing point), the other was distorted to some extent determined by the staircase procedure. The order of the distorted stimulus was randomly determined. On any trial of the sequence, a subject saw a large numeral 1, followed by a stimulus object, then a mask, then a large numeral 2, followed by the second stimulus. Observers merely indicated whether the first or second stimulus was distorted.

Using this procedure we were able to crudely estimate sensitivity to distortion. The average value of distortion which corresponded to the d' - .707 point was magnification equal to 2.8 for compression, and magnification equal to 0.33 for expansion. Thus, virtual space had to be compressed or expanded by a factor of 3 in order for observers to discriminate a shape distortion at this low level of sensitivity. In addition, there was a great deal of intra-subject variability. Across sequences the estimates varied widely. For example, the distortions equal to d' - .707 ranged from magnifications of 1.4 to 3.0, and from minifications of 0.1 to 0.9. Thus sensitivity is not only poor, but highly variable as well. The data presented in Table 1 for Experiment 1 show a close relationship between distortion and judgment with unfamiliar objects. Familiarity apparently greatly reduces discrimination ability.

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